TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

STEFANUS ARINNO WIRDATMADJA

MICROFLUIDIC COMMUNICATIONS PROTOCOL DESIGN AND TRANSMISSION PERFORMANCE ANALYSIS

Master of Science thesis

Examiner: Prof. Yevgeni Koucheryavy,
Dr. Sasitharan Balasubramaniam, and
Dr. Dmitri Moltchanov
Examiner and topic approved by the
Faculty Council of the Faculty of
Computing and Electrical Engineering
on 20th November 2014

ABSTRACT

STEFANUS ARINNO WIRDATMADJA: Microfluidic Communications Protocol Design and Transmission Performance Analysis
Tampere University of Technology
Master of Science thesis, 47 pages
November 2014
Master's Degree Programme in Electrical Engineering
Major: Wireless Communication Circuits and Systems
Examiner: Prof. Yevgeni Koucheryavy, Dr. Sasitharan Balasubramaniam, and Dr. Dmitri Moltchanov
Keywords: microfluidics, nano communications, networking, protocols, SER, throughput

The new field of nanocommunications aims to develop communication systems at the nanoscale. It has developed into two main communication directions: *molecular communications* and *electromagnetic communications*. Microfluidic communications is a subtype of molecular communications. Existing liquid based microfluidics applications are the main target for the integration of a communication feature.

Currently, there are still no standards for microfluidics communications protocol. The protocols should consider particular phenomena such as noise, transmission access priorities, and probability of coalescence between microdroplets. Those phenomena bring challenges in protocol development of microfluidics communications.

In this thesis, the protocol stack for microfluidics communications is developed. Starting from the physical layer, feasible modulation schemes for data transmission suitable for microfluidics communications is examined. Later, medium access control layer protocols is discussed in order to optimize transmission medium access for the network entities. This is done to avoid droplet coalescence. Specification of the addressing and routing methods is defined to ensure data submission to the destination point. Finally, the performance of the proposed schemes and numerical comparison to viable alternatives are analyzed.

The results of the evaluation are reached through MATLAB software simulations. This work concentrates on *Communication through Silence (CtS)* where the payload is represented as distance between two droplets. Two schemes of CtS (decimal and hexadeximal) are investigated. Both CtS schemes with particular optimum amount binary payload outperforms OOK in throughput performance. The fairness of the transmission system can be achieved for a decentralized system by combining slotted (TDMA) scheme and a probability-based algorithm.

PREFACE

This Master of Science thesis had been done in the Nano Communications Center, the Department of Electronics and Communication Engineering in collaboration with the Department of Automation Science and Engineering in Tampere University of Technology, Tampere, Finland from March 2014 to October 2014.

First of all, I would like to thank Prof. Yevgeni Koucheryavy for giving me the opportunity to join the project. Moreover, my research have gone this far due to his moral support and guidance.

I would also like to thank Dr. Sasitharan Balasubramaniam for acting as my supervisor. I am grateful to him for introducing me to this research area that I had not considered before. His guidance, suggestions, and critiques in in the completion of this thesis were very significant.

Furthermore, I would like to thank my supervisor, Dr. Dmitri Moltchanov who has supported me with technical guidance and knowledge in this research. I am indebted to him for his advice, guidance, and counsel.

Additionally, I would like to send my gratitude to the Department of Automation Science and Engineering at TUT. The team that has supported me with data and information included in this thesis includes Paul Bolcos, Jari Valiaho, Joose Kreutzer, and Prof. Pasi Kallio.

Finally I would like to thank my family in Indonesia, my rowing team (Tampereen Akateemiset Soutajat), my jiu-jitsu club mates (Tampereen Ju-Jutsukoulu), and friends for being helpful and supportive during my study at TUT.

Tampere, 20.11.2014

Stefanus Arinno Wirdatmadja

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

BER	Bit Error Rate
CDMA	Code Division Multiple Access
CSMA	Collision Sense Multiple Access
CtS	Communication through Silence
CU	Central Unit
CYTOP	Cyclized Transparent Optical Polymer
DI	Deionized
DNA	Deoxyribonucleic Acid
EDL	Electric Double Layer
HOL	Head of Lines
IF	Interface
IPA	Isopropyl Alcohol
LED	Light Emitting Diode
LOC	Labs-on-Chip
MAC	Medium Access Control
MFC	Microbial Fuel Cell
OOK	On Off Keying
OSI	Open System Interconnection
PB	Piggyback
PDMS	Polydimethylsiloxane
PPM	Pulse Position Modulation
SER	Symbol Error Rate
SNR	Signal-to-Noise Ratio
SSS	Single Start Stop
TDMA	Time Division Multiple Access
Teflon AF	Teflon Amorphous Fluoropolymers
TUT	Tampere University of Technology

A	channel cross-sectional area $[m^2]$
D_{10}	total delay corresponding to n-bits payload between the Start and Stop symbols for decimal base $[s]$
D_{16}	total delay corresponding to n-bits payload between the Start and Stop symbols for hexadecimal base $[s]$
D_H	hydraulic diameter $[m]$
F_c	operating clock frequency $[Hz]$
G	throughput $[bps]$

L_b	width of droplet $[m]$
L_d	length of payload $[m]$
$L_{d_{max}}$	threshold of payload length $[m]$
L_min	minimum distance between droplets to avoid droplet coalescence $[m]$
L_T^i	required vacant space for transmission $[m]$
p	wetter perimeter $[m]$
P	pressure $[Pa$ or N/m^2 or $kg/m \cdot s^2]$
P_{10}	decimal-based data representation
P_{16}	hexadecimal-based data representation
$P^{(i)}$	priority of station i
Q	volumetric flow rate $[m^3/s]$
R	gas constant $[J/mol \cdot K]$
R_{10}^{PB}	data rate for piggyback scheme, decimal base $[bps]$
R_{10}^{SSS}	data rate for single start stop scheme, decimal base $[bps]$
R_{16}^{PB}	data rate for piggyback scheme, hexadecimal base $[bps]$
R_{16}^{SSS}	data rate for single start stop scheme, hexadecimal base $[bps]$
$R^{[OOK]}$	data rate for on-off keying $[bps]$
Re	reynolds number
T	temperature $[K]$
T_b	time slot duration $[s]$
T_c	operating clock period $[s]$
T_{cs}	time duration of carrier sensing $[s]$
T_{sync}	time duration of synchronization slot $[s]$
T_min	minimum delay period to avoid droplet coalescence $[s]$
v	average velocity of the fluid $[m/s]$
V	volume $[m^3]$
Δ_{T_b}	one length increment unit of address $[s]$
μ,η	dynamic viscosity $[kg/m \cdot s$ or $Pa \cdot s]$
ν	kinematic viscosity $[m^2/s]$
ρ	density of the fluid $[kg/m^3]$
γ	surface tension $[N/m]$
θ	contact angle $[radians]$
κ	curvature of free surface
σ_P^2	variance of pressure-maintenance noise
σ_I^2	variance of injection-inaccuracy noise
σ_D^2	variance of detection noise
σ_E^2	variance of overall system noise

1. INTRODUCTION

Over the past few decades, communication systems have undergone tremendous evolutionary changes. The expansion of communication systems has witnessed connectivity between various types of technologies, ranging from large-scale wired networks (e.g. optical networks) to various wireless network technologies (e.g. WiFi and Cellular systems). The advancements of communication networks have also moved towards connection of small-scale sensor networks, where devices can be embedded in the environment, or in/on the body (e.g. Body Sensor Networks). However, in recent years, the advancement of communication systems has begun to witness the emergence of new paradigms. One example of this new paradigm is *molecular communication* [2], [5], where communication networks are constructed from nano-scale biological components that are found in nature. This new paradigm shift is not only limited to biological systems, but has also incorporated communication into media found in man made micro and nanostructures. An example is the communication in *microfluidic* devices. Microfluidic devices have numerous applications in the field of biotechnology as well as molecular biology. Examples of applications in the field of microfluidics are *Labs-on-a-Chip* (*LOCs*) [6] biomolecule synthesis [22], biomolecule detection [23], *Deoxyribonucleic acid (DNA)* sequencing [1], and development of digital microfluidic implementations in biochips [4].

Microfluidic engineering is a multi-disciplinary field that aims to manipulate fluid at small volumes. Through the manipulation of flow within the microchannels, communication researchers in recent years have begun to investigate the possibility of transmitting information through the fluid flow. The need of communication also expands to chemical and biological fields in order to facilitate more effective and efficient processes via integration of automation to the system. In some chemical and biological analysis, all involved components should be biocompatible in accordance with biomedical standard. The example of undesired electromagnetic effect is the modification of behavioral response of cells to drugs. In this case, the cell behaves differently due to a disturbance of its plasma membrane as a result of exposure to electric pulses [10]. Another example is irreversible electroporation of a transmembrane transport of molecules. This occurs due to strong electric field pulses which cause cell death and lysis [8]. Microfluidics is an option for realizing such a communications system.

1.1 Microfluidics

Microfluidics is a system commonly used in biology and chemistry fields for performing experiments involving fluid substances. The system can be imagined as a miniature pipe with fluid flowing through it, carrying different fluids from one point to another. The ability to perform tasks with a small amount of fluid and extremely small pipes make the process efficient and appealing in a number of applications. These systems can be efficiently used to move various substances between different compartments. Microfluidics plays an important role in many application due to its efficiency in analyzing small volume accurately, at a low cost, and low energy consumption due to its size. Moreover, flow in microfluidic system is mostly in a laminar regime. It is very difficult to achieve turbulent flow in microfluidics due to the small size of hydraulic microchannels.

According to the number of fluids flowing in it, microfludic flows can be categorized by single phase flows or two phase flows. In single phase flows, there is only one continuous phase in the system. On the other hand, in two phase flows, a small volume of fluid is manipulated (commonly termed as *droplet* or *dispersed phase*) and the carrier fluid is called a *continuous phase*. It is further categorized into *digital* and *droplet* microfluidics. In this thesis the focus is droplet microfluidics.

Two phase flows can be utilized for communication purpose because of a similarity to conventional electrical communications. From the communications perspective, microdroplets represent the transmitted information propagating through a certain transmission medium whose chemical substance or physical characteristics are different. A microdroplet generator and a pump act as a transmitter and coder which control the generated information. The microdroplet sensor on the receiver functions as a detector which detects the microdroplets passing through the detection area.

Furthermore, based on the way microdroplets are handled, microfluidic systems can be classified into two categories: *digital* and *droplet* microfluidics, as illustrated in Fig. 1.1.

1.1.1 Droplet Microfluidics

Droplet Microfluidics is categorized as a multi-phase system since it has at least one continuous phase and one dispersed phase flowing in a microchannel. Ensuring

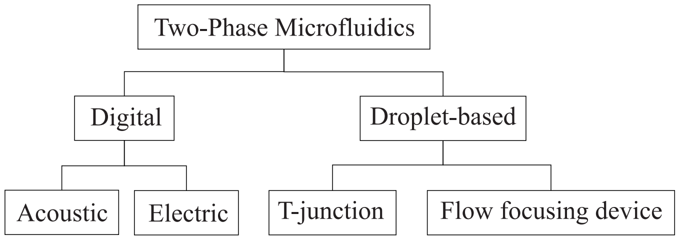


Figure 1.1 *Classification of two-phase microfluidics systems.*

laminarity of the flow (characterized by low values of *Reynolds* number) is crucial to avoid turbulence in the channel. This imposes strict limitations on the flow velocity and eventually the transmission rate of the system. The illustration in Fig. 1.2 shows the droplet microfluidics whose channel height is h and utilizes the syringe pump as the flow controller, the T-junction as the microdroplet generator, and a laser-based opto-detector as the microdroplet detector.

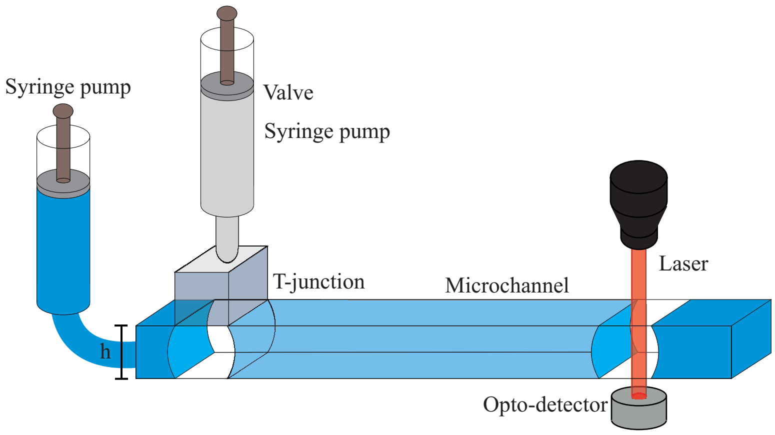


Figure 1.2 *Illustration of a droplet microfluidics system.*

1.1.2 Digital Microfluidics

Digital Microfluidics is a system where acoustic or electric control is required to move a droplet. The popular approach is based on *Electrowetting on Dielectrics* (*EWOD*) which enables changes on the hydrophobicity level at various sections of the plane. The plane utilizes a thin layer of a specific material such as *Teflon AF*, *FluoroPel V-polymer* or *CYTOP* as well as electric fields to manipulate the hydrophobicity level. Fig. 1.3 illustrates the digital microfluidics system with two droplet injectors (transmitters) and two droplet collectors (receivers).

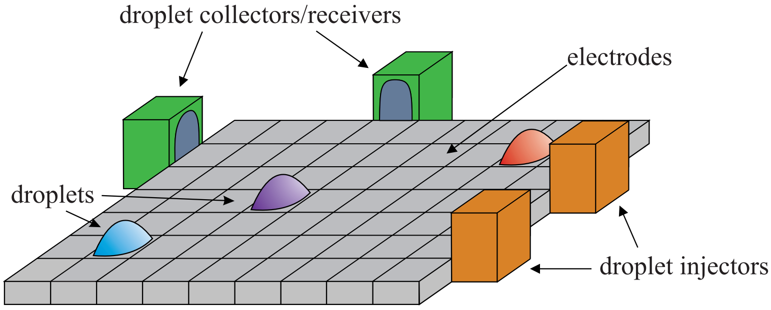


Figure 1.3 *Illustration of a digital microfluidics system.*

1.1.3 Physical Transmission Medium

The physical transmission channel in microfluidic communications depends on the characteristics of the constituent material. There are two types of channels based on the material's wetting properties relative to the type of fluids used (see Fig. 1.4):

- *Hydrophilic Channels* result in the liquid's contact angle being smaller than $\theta = 90°$ when the microchannel is exposed to the liquid.
- *Hydrophobic Channels* result in the liquid's contact angle being larger than $\theta = 90°$ when the microchannel is exposed to the liquid.

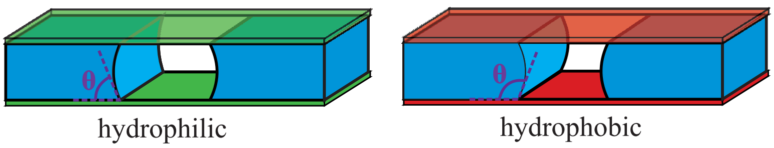


Figure 1.4 *Illustration of hydrophilic and hydrophobic microchannel types.*

The form of droplets for these two channels is shown in Fig 1.4. *Polydimethylsiloxane* (*PDMS*) is commonly used to build a microfluidic communication channel since it is easy to work with, non-toxic and harmless to the environment. PDMS is naturally hydrophobic, but can be made hydrophilic via plasma oxidation treatment. Furthermore, long-term hydrophilization can be achieved by combining plasma and chemical treatment [18]. Hydrophobic channels require larger amount of pressure than hydrophilic channels for liquid droplet pumping. Additionally, dispersed and continuous phase choice affect the pressure and system behavior. When applying the pressure, the compressibility factor should also be taken into account since it may affect the volume changes along the channel. Compressibility is an issue when either the dispersed or continuous phase is gas. Compressibility can also influence the length of the bubble. Therefore, these various properties including the number of droplets and the volume ratio between the dispersed and continuous phases will impact the speed at which the fluid flows in the channel, which in turn will affect the data rate of the channel.

Another challenging characteristic of the microfluidic system is the data transportation flow. In a single channel, it is unidirectional following the direction of the flow. In order to provide a full duplex system one needs to implement two channels running in parallel. This affects the complexity of the system, imposing additional requirements in its design. In particular, when two directional exchange of data is required each end system must be connected to both forward and reverse channels. However, one solution to this constraint is to create ring-shaped topology, but this results in additional delay when messages travel around the entire ring.

1.2 Point-to-Point Communications

In any digital transmitter-receiver communications system, there are three important elements which can increase the system's efficiency and reliability. These are the source coder, channel coder, and the modulator (illustrated in Fig. 1.5). The roles of these elements complement each other in a digital transmission system. Their functionalities can be adopted for droplet microfluidic communication system.

- *A Source coder/decoder* compresses the data by exploiting redundancy in the existing alphabet (known as lossless compression). The ultimate goal is to achieve lower bit-rates. When prior knowledge of data transmission probability is available, source coding (e.g. Huffman codes) can be of special importance in microfluidic communications; achievable rates of the prospective systems are expected to be fairly low while each droplet injected to the channel adds to the instability of the system, causing the pressure change that must be further compensated by the pressure pump.

- *A Channel coder/decoder* is responsible for concealing errors that may occur during the transmission/detection process by introducing some degree of redundancy to the compressed data. In principle, there are no restrictions on the choice of channel codes in microfluidic communications. However, keeping in mind the simplicity requirements of the end nodes, simple channel codes such as parity check codes may be sufficient.

- *A Modulator/Demodulator* converts digital data to analog form which fits the properties of the transmission channel. In microfluidic systems, this modulation can be realized by manipulating both the physical and chemical properties of the microdroplet. The manipulated properties can be size, color, or chemical substance. The traditional *On-Off Keying (OOK)* scheme works well in the microfluidic system. One microdroplet can represent digital bit "1" and non-existence of the microdroplet can represent a digital bit "0". Another example of a modulation scheme that can be adopted for the microfluidic system is the *Pulse Position Modulation* (*PPM)* which represents bits "1" and "0" based on the relative distances between the microdroplets. In addition to the two previously mentioned schemes, *Communication through Silence (CtS)* can also be an option through exploitation of different base numbers, for example decimal or hexadecimal, for data transmission purposes.

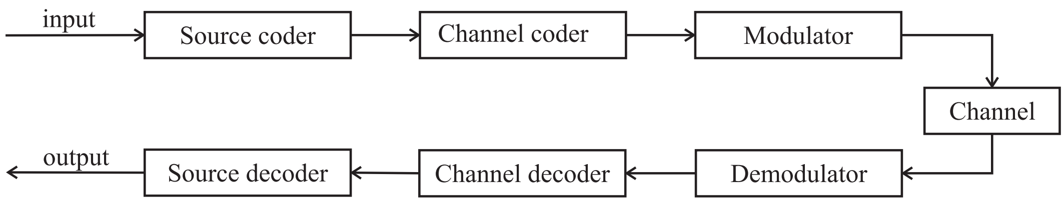


Figure 1.5 *Digital communication system block diagram.*

1.3 Related Studies

The communications capabilities of microfluidics can be used either as a complementary feature of the original function of an application or as the main feature itself. As a complementary feature, microfluidics may help to speed up the performance of the main process and/or support an automation process in the corresponding system. Communication as a main feature can be implemented in those applications where classic electromagnetic communications cannot be used due to the various specifics of system interfaces.

The current implementations of microfluidics in practical applications are mainly found in the fields of chemistry and biology helping to perform various tasks such as DNA sequencing [1], drug delivery, and diagnosis of diseases. Some of the applications may need to employ biocompatible elements in the microfluidics system due to the sensitivity of the analyzed molecule to electromagnetic exposure. Networking concepts such as the switching mechanism proposed in [11] is used to support the existing functionalities of microfluidics applications. It supports the restriction of using only pressure manipulation to choose the right path without utilizing any electro-magnetic elements.

A routing algorithm is also proposed in [25] for digital microfluidic biochips. The purpose of the developed system is to manage the traffic of microdroplets on the biochip to avoid cross contamination and to reduce the droplet transportation time. Cross contamination occurs when two microdroplets' routes intersect each other and when the residue of the previous droplet remains in the channel/path. This routing algorithm helps to improve the overall biochip performance and enhances its application scope.

The droplet microfluidics system can possibly be implemented using the *EcoBot* concept [19]. The proposed system is intended to collect the biochemical sources of energy from the environment and transport them to the *Microbial Fuel Cell* (*MFC*) to be converted to electricity. The transportation mechanism can be implemented as a droplet microfluidics system. In addition to transferring the source of energy, the available transportation channel may also be used for information transfer to different parts of the EcoBot.

When the microfluidic system is utilized as a stand-alone communication system, various biocompatible communication systems become feasible. One may need such a system when it is desirable to reduce the number of electromagnetic-based components due to the specific restrictions of the application. The applicability of microfluidic communications to a specific task must be carefully addressed at the system design phase due to various restrictions on system performance. While there no definitive quantitative results have been published, it is expected that such systems would provide rather limited data rates of up to tens of Kbps and relative delays up to few seconds.

Fluidic communications can also be implemented on a larger scale than at the micro or nano levels. One may think of a system having channels of up to few centimeters in diameter that may contribute to a specific application. While the assessment of such systems is outside the scope of discussion in this thesis, it must be mentioned that the properties and behavior of macrofluidics system can be substantially different.

1.4 Challenges and Motivation

Microfluidic communications is still in a state of infancy where there are still many possible research opportunities. The development of microfluidics from the communications perspective has not emerged yet which means each application needs to develop its own standard protocols. Therefore, in this thesis, protocols for microfluidic communications will be defined so that in the future it can support microfluidic application developers, leading to the integration of various applications and collaboration. The protocols that are defined include physical and medium access control layers which consider the physical properties of fluid and transmission microchannels, available hardware limitation challenges and opportunities, and adoption of feasible concept from conventional electromagnetic communications. Additionally, noise characterization, *symbol error rate (SER)* analysis and achievable *throughput* of different scheme implementations are performed since these aspects are crucial in determining the communication system reliability.

2. DROPLET MICROFLUIDIC SYSTEMS AND THEIR COMPONENTS

Comparing the characteristics of droplet and digital microfluidics systems in 1.1, one may notice that droplet microfluidics resembles a number of essential features of a general purpose communication system including propagation medium (microchannel), clearly defined signal type (dispersed phase), carrier (continuous phase), on-the-fly generation and detection of bubbles, etc. Microfluidic channels can be further concatenated by special equipment such as a microfluidic router to form a network. Furthermore, in digital microfluidics, the electrodes along the transportation plane should be fully controlled by activating particular electrodes on the desired path to direct the microdroplet to the destination point. Such control processes make the system complex and suitable for applications where each section of a transmission channel/plane is able to be managed by one central controller. Meanwhile, in droplet microfluidics, the transmission channel is an independent entity that is not required to be fully controlled by a special device. Taking into account its implementation simplicity and low cost, droplet microfluidics is expected to have a much wider range of applications that could integrate communication features, especially due to its similarity to classical communication components where the transmission channel is not controllable. For this reason the components of droplet microfluidics for communication will be further studied.

2.1 Microfluidics Properties

Design of microfluidic devices is based on the continuum concept of fluid mechanics, where matter is continuously distributed according to the same principles as in macro-scale fluid mechanics. Fluid flow in microfluidic devices can be in one out of three regimes: (i) laminar flow, (ii) turbulent flow and (iii) transition phase. An ideal microfluidic channel should maintain the *laminar flow* regime as turbulent effects may negatively affect the system performance. The dimensionless parameter describing the flow regime is the *Reynolds number*, (Re). A flow is in the laminar state if $Re \leq 2000$ which means the flow's sublayers have no lateral mixing. For *turbulent flow*, $Re \geq 3000$, the flow is characterized by chaotic properties. The flow regime whose Re lies between 2000 and 3000 is defined as transition phase in which the flow can be either laminar or turbulent depending on flow uniformity and surface roughness of a channel. Small scale and low velocity flows tend to be in laminar regime. On the other hand, large scale and high velocity flows have more possibility to be in turbulent regime. When the liquid with kinematic viscosity $\nu\ m^2/s$ flows in a channel with a diameter $D_H\ m$ (assuming cylindrical channel) at a rate of $v\ m/s$, the Reynolds number can be calculated according to the equation:

$$Re = \frac{vD_H}{\nu}. \tag{2.1}$$

The water that is utilized as a continuous phase in this work is a Newtonian fluid which means that viscous stress is always proportional to local strain rate. In other words, viscosity does not change under the shear or tensile stress. A steady laminar flow of Newtonian fluid depending solely on the applied pressure is characterized as *Poiseuille* flow. Therefore, the pressure change along the channel can be calculated according to the equation:

$$\Delta P = \frac{128\eta L}{\pi D_H^4} Q, \tag{2.2}$$

where ΔP is a pressure loss (Pa), L is the channel length, η is dynamic viscosity ($Pa \cdot s$), d is the diameter of the channel (m), and Q is volumetric flow (m^3/s) estimated as follows:

$$Q = \lim_{\Delta t \to 0} \frac{\Delta V}{\Delta t} = \frac{\mathrm{d}V}{\mathrm{d}t} = \iint_A v \cdot \mathrm{d}A \tag{2.3}$$

In this thesis, air is used as a dispersed phase. When an air droplet enters the channel, the pressure change no longer follows Eq.(2.2) and additional pressure components to compensate total pressure change are required. The pressure drop components now consist of capillary force pressure and friction force pressure. The capillary pressure is defined as the difference in pressure across the interface between two immiscible fluids. Since there are two interfaces, receding and advancing, there are two pressure differences. Thus, [3]

$$\begin{aligned} \Delta P_{total} &= \Delta P_{capillary} + \Delta P_{friction} \\ &= \frac{4\gamma}{D_H}(\cos\theta_{d,r} - \cos\theta_{d,a}) + \frac{128Q}{\pi D_H^4}(\eta_{air} L_{air} + \eta_{water} L_{water}) \end{aligned} \tag{2.4}$$

and the dynamic contact angle θ_d is defined as

$$\theta_d = \theta_s + \frac{\kappa\eta v}{3\gamma\theta_s^2} \tag{2.5}$$

Theoretically, the minimum size of the air droplet is equal to the size of the diameter of the microchannel [15]. However, the size of the droplet is prone to breakage by flow pressure (even if it is laminar) causing water flow through the path between channel wall and droplet. In order to prevent this, the size of the droplet must be larger. In addition, the minimum distance between droplets must be considered as well since droplet coalescence might occur when the distance between droplets is less than the minimum distance [16].

In Fig. 2.1, it is evident that the smaller diameter of microfluidic channel, the higher the limit of flow speed necessary to maintain its laminar regime. The area below the purple dashed line ($Re \leq 2000$) indicates that the flow is still laminar for the microchannel diameter and flow speed pair. For example liquid flow speed of 40 m/s is still laminar in a 50 μm channel, but it is turbulent in a 100 μm channel.

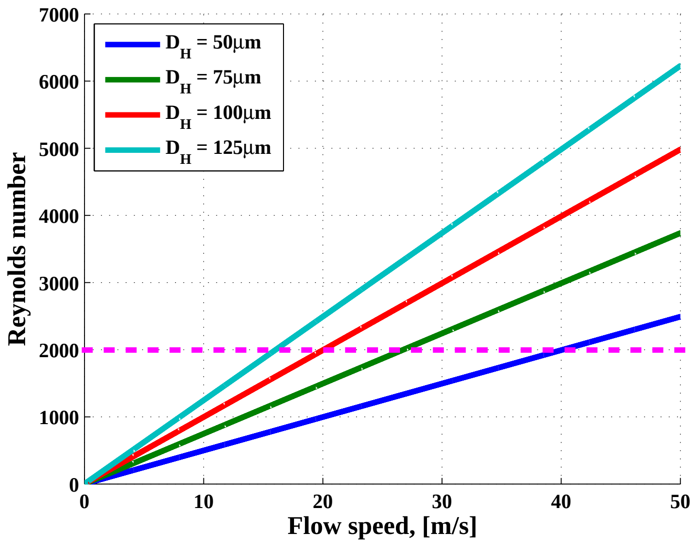


Figure 2.1 *Reynolds number for different channel diameters and flow speeds.*

In contrast to water which is incompressible, air is categorized as a compressible liquid. In a condition where the temperature is T^o K and absolute pressure is P Pa, most gases with n $moles$ of chemical substance, have a volume V m^3 which follows this ideal state equation:

$$PV = nRT \tag{2.6}$$

where R is the gas constant (8.3144621 $J/mol \cdot K$).

In a microfluidic system, the assumption of an isothermal state can be applied. In isothermal conditions, when gas (in this case, an air droplet) flows along a channel with pressure changes, the volume of the gas expands/compresses according to the following equation:

$$V_2 = V_1 \frac{P_1}{P_2} \tag{2.7}$$

While travelling along the microfluidic channel, air droplets experience pressure drops caused by pressure difference between the inlet (higher pressure) and the outlet (lower pressure). Consequently, the volume of the air droplet expands and it should be considered during the droplet detection process. Moreover, droplet lengths and duration measurements are estimated at the location of the detectors on the design process.

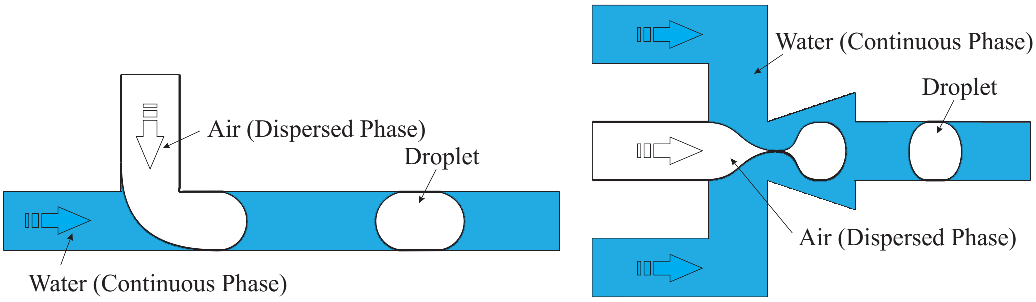
2.2 Components

In microfluidics communication system, the microchannel must be equipped with three main components. They are the droplet generator, the droplet detector, and the flow controller. Each components has several implementation alternatives that need to be selected based on system requirements. Below a short description of possible solutions for each system components is presented.

2.2.1 Droplet Generation

The microdroplet can be generated by the combination of channel geometry and the valve. The channel geometry specifies how the dispersed phase can be formed with respect to the continuous phase. There are two types of microdroplet generation system proposed so far. These are the *T-junction* and the *flow focusing device.*

- *A T-junction* (Fig. 2.2(a)) employs one inlet for the dispersed phase and another one for the continuous phase. The junction of the two inlets forms a 90° angle to each other. This microchannel geometry should ensure the precise breakup for certain volume of liquid to form the desired droplet size.
- *A Flow Focusing Device* (Fig. 2.2(b)) generates the droplet by positioning the inlet of the dispersed phase in the middle of the continuous phase inlets, in line with the microchannel.



(a) T-junction. (b) Flow focusing device.

Figure 2.2 *Droplet generator mechanism.*

In addition to the channel geometry, the valve also plays an important role in determining the droplet size and preventing any back pressure. A *Solenoid* valve is an electromechanical valve which is popular due to its low cost, simplicity, and reliability. A *Piezoelectric* valve is more efficient in terms of power consumption, provides higher operating frequencies, and is more precise during operation as the valve can be opened (deformed) proportionally to the given electric charge [26].

2.2.2 Droplet Detection

In microfluidics-based communication, proper detection of the microdroplets is required to obtain the correct transmitted message/data. Miniaturized devices are required in order to support this task, in addition to a high level of spatial resolution, high speed, and sensitivity. The following techniques have been proposed as methods for droplet detection:

- *Optodetection* is based on light passing through the microchannel [7]. The detector measures the light intensity as the liquid flows between the light source and the detector. The light source can be laser, LED (light emitting diode), or other light emitting device. An optodetector should be embedded to a single node (a node in this context refers to either the *transmitter* or the *receiver*) that is attached to the channel.

- *Electric Detection* can be either capacitor [12] or resistor [17] based. Capacitor-based detectors exploit the difference in dielectric constants of the liquids and are generally more simple and accurate compared to the resistor-based approach. Similar to optodetectors, the electric detector should be an integral part of each node.

- *Imaging detection* analyzes images captured by high speed cameras [14]. This detection method requires a high-speed camera along with complex post-processing techniques. Both the dispersed and continuous phases must be clearly distinguishable in visible light. In contrast to the opto- and electric-based detection, the image-based detection is carried out by a central control entity, which limits its applications in droplet microfluidics.

2.2.3 Flow Control

Droplet microfluidics is a flow based system, where controlled pressure is one of the key factors to ensure operational stability. Uncontrolled pressure may lead to both quantitative and qualitative errors in droplet detection. It may also result in flow rate fluctuation causing noise and subsequent errors in the detection and data analysis. Therefore, it is important to understand several techniques of pressure/flow control management as described below:

- *Gravity-Driven Hydrostatic Pressure* exploits solely the height difference between nodes. The simple implementation is based on positioning the liquid reservoir at a certain height in order to allow the force of gravity to generate flow.

- *Pressure Pumps* manage the pressure inside the reservoir to generate the desired flow. The resulting flow is more stable compared to other techniques. Such an apparatus can be controlled by computer resulting in a more stable, precise system.

- *Syringe Pumps* are based on a mechanically applied force to drive the flow rate. Such a pump typically generates an undesired pulsation and flow oscillation, especially at low flow rate. Different flow rates can be achieved by adjusting the linear speed of the mechanical system that pushes the syringe or by altering the syringe volume.

- *Peristaltic Pumps* utilize rotors to pump the fluid while continuously squeezing the flexible tube in a rotational direction. The pulsation of the flow rate cannot be avoided using this type of pump. Different flow rates can be achieved by adjusting the rotational speed or changing the size of the flexible tube where the liquid flows with the corresponding diameter size.

- *Electro-osmotic Pumps* produce liquid flow by applying an electric field on the *Electric Double Layer* (*EDL*).

- *Reciprocating Diaphragm Micropumps* are composed of reciprocating diaphragms which can be piezoelectrically actuated. This structure is connected to a synchronized inlet valve (attached to liquid reservoir) and an outlet valve (attached to microfluidic channel) to generate the desired flow.

3. MICROFLUIDICS COMMUNICATIONS

Microfluidic systems bring their own specific properties to the implementation of the abovementioned subsystems (Sec. 1.2), making classical communication solutions non-optimal. For source coding implementation, the input alphabet and the prior knowledge of the data transmission probability are needed to produce effective codewords. To implement channel coding, a tradeoff between reliability and redundancy bits can be a limitation since more injected bits result in higher pressure drops. From this perspective, the communication through silence concept that only uses two droplets to represent any transmitted symbol, could provide a viable alternative to classical digital modulations such as OOK or PPM [21]. It is important to note that in microfluidic communications, microdroplet property manipulation for modulation is limited not only by the availability of variants and pressure fluctuations, but also by injector and sensor technologies.

Another important feature of the physical layer is the detection of the droplets. As discussed previously, it could be implemented using a number of different approaches. It is necessary to rely on localized decision methods such as optodetection or capacity/resistivity based electric detection. In both cases the droplet can be detected using two approaches: based on instantaneous change in the measured metric (e.g. capacitance) or based on integrated metrics. The latter approach is similar to received power detection that is conventionally used in electromagnetic communications, and is expected to be more reliable despite introducing detection delay. The former approach is supposed to be faster but less reliable as noise in the measured metrics may lead to false droplet detection. It is faster since it does not require complex data processing and it is less reliable when the level difference between lower and upper level of measured metrics is small enough that noise fluctuation over threshold may lead to a false decision [12] [13]. A threshold-based method should be used to detect the droplet. This threshold could be obtained using a methodology similar to what is used in classical communication systems, accounting for the form of the transmitted signal and all the noise affecting the measured parameter.

For microfluidic systems, the difference in the considered metric for the dispersed and continuous phases needs to be relatively large to be distinguishable. In other words, either well distinguished phases or highly sensitive sensors are needed. The raw detection output may or may not be sufficient for further data processing. Various post processing techniques such as filtering can suppress the effect of noise, thereby improving the resulting *signal-to-noise ratio (SNR)*.

3.1 Protocol Stack

In this thesis, the protocol stack for microfluidics communications is proposed. First, protocol stack functionalities will be described following the first two layers of the open system interconnection (OSI) X.200 model [20]. Then, starting from the physical layer, various communications mechanisms and their performance will be analyzed. Furthermore, comparison to other alternatives will be studied.

The illustration of the droplet microfluidics communications protocol stack is depicted in Fig. 3.1. The physical layer is responsible for raw data representation for the transmission through the microchannel. In order to do that, an efficient modulation scheme is needed. To make guided decisions on these functionalities, it is necessary to assess the noise sources affecting the detection process and then estimate throughput and *bit error rate (BER)* provided to upper layers. At the *medium access control (MAC)* layer, medium access control protocols are developed to regulate the way transmitters accessing the transmission medium avoiding coalescence of droplets. Both centralized and semi-random access schemes are addressed, assessing their performance in terms of the number of supported stations and the rate share they receive. Additionally, addressing and switching methods are determined ensuring the delivery of data packet to the correct destination in the microfluidics network. Note that error correction is omitted. This is because classic forward error correction mechanisms can be employed in microfluidics. Automatic repeat request protocols are also feasible if duplex communication is provided.

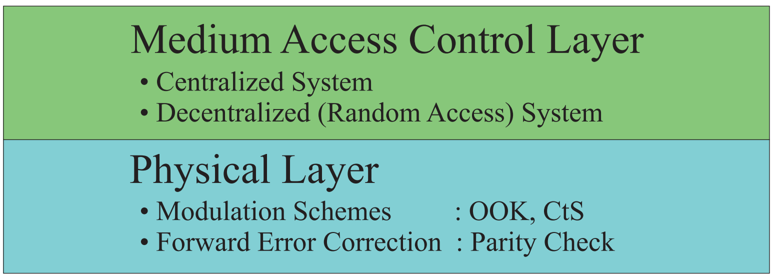


Figure 3.1 *Protocol stack for microfluidics communications.*

It is important to note that in this work, upper layer functionalities such as end-to-end reliable delivery of the transport layer or applications layer protocols are not addressed. This is because the first implementations of microfluidics networks are expected to be localized subnetworks consisting of single channel and may not require network layer functionalities. In this case, two lower layer functions are sufficient to create a network. Furthermore, end-to-end retransmissions in microfluidics networks may cause extremely long delays implying that error correction features must be concentrated at the medium access control and physical layers. Nevertheless, both the addressing and the routing of droplets are still needed when local networks of microfluidic channels are considered. Finally, the application layer functionality is too specific to define at this early stage of development.

3.2 Physical Layer

In microfluidics communications, water flow performs the role of transmission medium. Similar to electromagnetic communications, the transmitted data can be represented using different kinds of modulation schemes. The modulation scheme should maximize the data rate and maintain the error rate as small as possible. Two modulation schemes are considered as candidates for information transmission in microfluidic networks. These are *on-off keying (OOK)* [24] and *communication through silence (CtS)* [27].

3.2.1 Modulation Schemes

On-Off Keying

The most common elementary communication form uses the presence or absence of symbols to convey bits through a communication channel, known as *On-Off Keying (OOK)*. In the case of microfluidic channels, the bit "1" can be represented by a dispersed phase, while the bit "0" can be represented by a continuous phase of fluid. In OOK, the time required for a complete message to be transmitted depends on the amount of bits in a message, time slot duration, T_b, and the flow speed, v. In this thesis, the "message" and "payload" terms are used interchangeably, meaning the dispatched data by the transmitters in microfluidic communication system.

Communication through Silence

The *Communication through Silence (CtS)* is a modulation scheme that utilizes the delay between the *Start* and the *Stop* bits to convey the information through the

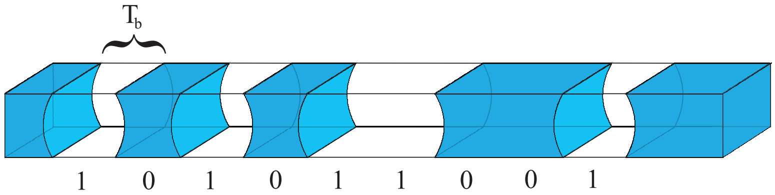


Figure 3.2 *Illustration of OOK modulation for microfluidics.*

communication channel. The process involves sending a Start bit to a receiver. Upon reception of this bit, a counter is started at the receiver. The assumption is that the operating frequency of both the transmitter and receiver are the same and the clocks are synchronized. As a result, the transmitter knows the step count of the receiver. Once the desired value of transmission is reached, the transmitter dispatches a Stop bit to the receiver to terminate the counting process. Therefore, the speed of transmission depends on the operating clock frequency, F_c.

It is important to note that the time slot duration of Start and Stop bits in CtS might differ from the time slot duration of a single digit, $T_c = 1/F_c$. Therefore, tuning of F_c is required to maximize the data rate of CtS by minimizing the T_c/T_b ratio as illustrated in Fig. 3.3. Another property of CtS that can be manipulated to increase the data rate is the base number of bits. For example, it has been demonstrated [9] that by transforming the values from decimal to hexadecimal base, one could increase the data rate of the scheme.

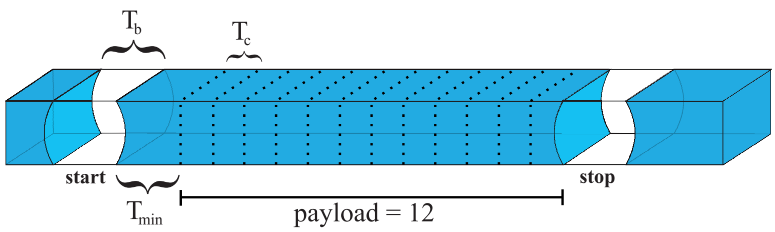


Figure 3.3 *CtS with decimal-based payload.*

In microfluidic communication system, the end-to-end delay includes the minimum delay, T_{min}, between the Start and Stop bits and the payload itself. The minimum delay could be equal to a single duration of a symbol, T_c. In what follows, it is assumed that the payload size is an integer multiple of the operating clock frequency of the system, F_c and the minimum delay, representing the value 0, and is set to exactly one clock period. From these requirements it is easy to see that clocks at the sending and receiving sides must be synchronized to avoid incorrect interpretation of the message in CtS.

The number-base format of the transmitted payload also affects the communication delay. Thus, the binary payload which is commonly used for machine-to-machine communications can be converted to other bases, e.g. decimal or hexadecimal, in order to maximize the data rate of the system and minimize the delay of a message. The choice of the number-base format not only dictates the duration of symbols but may require additional control sequences, e.g. a separator between digits. For example, for hexadecimal format three droplets resulting in three minimum gaps, $T_{\min}$ are needed. Meanwhile for decimal format, only two droplets resulting in two minimum gaps $T_{\min}$ are needed. Fig. 3.4 illustrates transmission of hexadecimal "U".

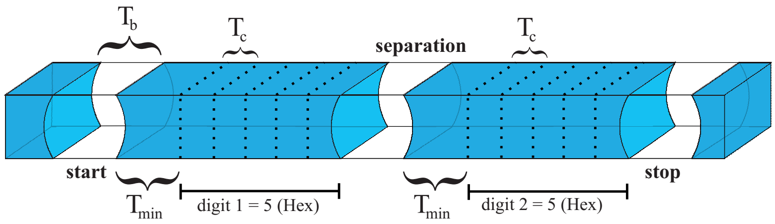


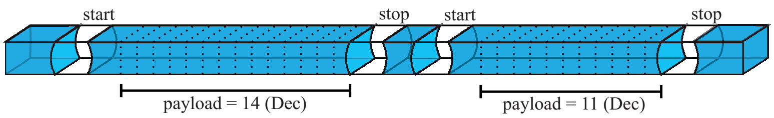
Figure 3.4 *Hexadecimal CtS transmitting ASCII character "U" (code="55").*

The procedure of continuous data transmission can also affect the achievable data rate of CtS. There are two ways to organize continuous transmission of data. According to *Single Start/Stop (SSS)* method, each payload has its own pair of Start and Stop indicators as illustrated in Fig. 3.5(a). Alternatively, one could use a more efficient *Piggyback (PB)* method, where two consecutive payloads have one common Start and Stop symbols as illustrated in Fig. 3.5(b).

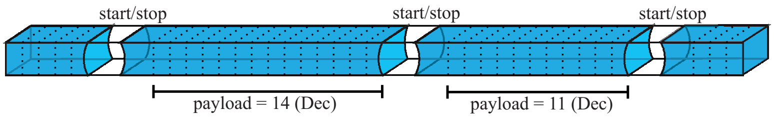
3.2.2 Detection Data Processing

In order to detect the bubble droplets, a suitable detection method should be used. The implementation of the detector should be precise to avoid misinterpretation of transmitted data. Exploiting electrical properties of fluids for detection purposes can be done by using a capacitor-based detector. There are two implementable detection method algorithms.

- *The Level-crossing method* utilizes the threshold level to determine the existence of water or air in the microchannel. On the border of two different liquids, the value of capacitance changes crossing the threshold value. This method is useful when the detected capacitance values for the two liquids have sufficient difference between each other so that the distinction can be clearly made. Moreover, the choice of threshold value should be carefully chosen to avoid false detection.



(a) Decimal CtS with single Start/Stop.



(b) Decimal CtS with piggyback.

Figure 3.5 *Communication through Silence (CtS) modulation scheme*

- *The Integrated metric method* integrates the detected values for a certain amount of time to avoid false detection due to additive system noise to detector output. This method has the advantage of detecting the border of two different liquids whose capacitance value difference is not so large, or when additive noises give sudden exceptional rise or drop to detector output.

The electrical property that can be used as a detection reference is capacitance. Capacitor-based detectors measures the material capacitance based on dielectric constant. In the case of air and water, the dielectric constants are 1.000589 and 80 respectively. This large difference indicates that detected capacitance value is distinguishable enough by using the level-crossing detection method. It is important to consider the fluids that are used for the system because it determines the processed output measurement of the detector. Fig. 3.6 shows the illustration of the capacitance-based detector output and the detection region definition on the corresponding threshold level.

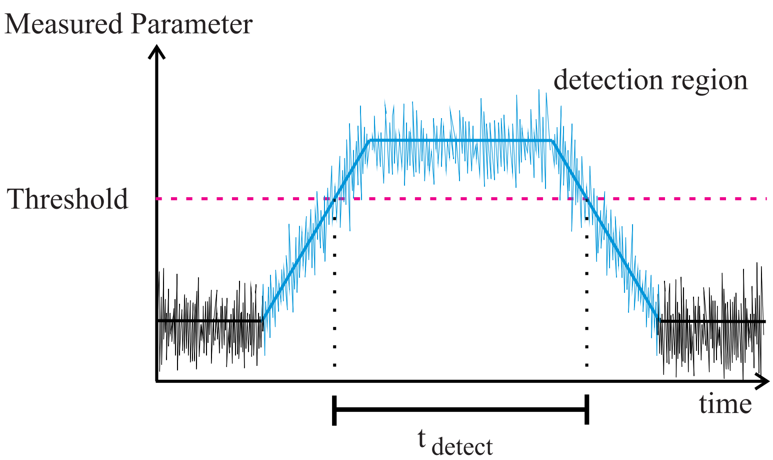


Figure 3.6 *Illustration of detector output with threshold detection level.*

3.2.3 Performance Analysis

The data rates for CtS and OOK differ. In the case of OOK, the maximum data rates are fully determined by physical constraints of the system, particularly, the minimum droplet size for a given channel diameter. On the other hand, CtS allows the rate to be controlled externally using the clock frequency of transceivers. For both modulation schemes, the value of the droplet duration, T_b, is related to flow velocity, v, and width of the droplet, L_b, as

$$T_b = \frac{L_b}{v}. \tag{3.1}$$

For OOK, both logical "1" and "0" have the same time slot duration T_b. Therefore, the data rate in bits per second (bps) can be computed as

$$R^{[OOK]} = \frac{1}{T_b} = \frac{v}{L_b}, \tag{3.2}$$

where n is the total amount of bits to be transmitted.

For CtS, the data rate depends on the number-base of data (e.g. decimal or hexadecimal) and the transmission method used (SSS or PB). When decimal base is employed, the total delay corresponding to n-bits payload between the Start and Stop symbols is

$$D_{10} = T_{min} + \frac{2^n - 1}{F_c} = T_{min} + \frac{P_{10}}{F_c}, \qquad n \in \mathbb{Z}^*, \tag{3.3}$$

where P_{10} is a decimal-based data representation and $T_{\min}$ is the time period which corresponds to minimum gap/distance between droplets to avoid coalescence.

Thus, for the SSS method the data rate is

$$R_{10}^{[SSS]} = \frac{n}{2T_b + 2T_{min} + \dfrac{2^n - 1}{F_c}} = \frac{n}{2T_b + T_{min} + D_{10}}, \tag{3.4}$$

while for the PB method the data rate is

$$R_{10}^{[PB]} = \frac{n}{T_b + T_{min} + \dfrac{2^n - 1}{F_c}} = \frac{n}{T_b + D_{10}}. \tag{3.5}$$

Another base to be considered is hexadecimal. A two digit hexadecimal number is sufficient to represent ASCII characters. The payload format should be different as each ASCII character is represented by two hexadecimal digits. Thus, an additional separation symbol is needed to separate the first and second digits in a number [9]. The total delay for n-bits payload between Start and Stop symbols is

$$\begin{aligned} D_{16} &= T_b + 2T_{min} + \frac{P_{10} - \left(15 \times \left\lfloor \frac{P_{10}}{16} \right\rfloor\right)}{F_c} \\ &= T_b + 2T_{min} + \frac{P_{16}}{F_c}, \qquad n = 0, 1, \ldots, 8. \end{aligned}$$

where P_{16} is a hexadecimal-based data representation.

For SSS method the question is

$$R_{16}^{[SSS]} = \frac{n}{3T_b + 3T_{\min} + \dfrac{P_{16}}{F_c}} = \frac{n}{2T_b + T_{\min} + D_{16}}, \tag{3.6}$$

while for the PB method the data rate is

$$R_{16}^{[PB]} = \frac{n}{2T_b + 2T_{\min} + \dfrac{P_{16}}{F_c}} = \frac{n}{T_b + D_{16}}. \tag{3.7}$$

3.2.4 Symbol error rate (SER) and throughput

The data rate provided by modulation schemes does not completely characterize their channel performance. In addition to maximizing the data rate, it is important to ensure that the BER is kept at an acceptable level. The latter requires consideration of factors affecting the reception of microdroplets at the receiving side. These factors add to the noise experienced at the receiving side. There are three types of noise affecting the reception of signals:

- *injection-inaccuracy noise:* The microdroplet injector/pump may be inaccurate in term of injection time and injected microdroplet volume/size. This error naturally leads to a bias in data detection at the receiving side. Particularly, this type of noise manifests itself in the deviation of droplet size and inter-droplet durations. The former effects affects performance of both OOK and CtS while the latter one is important for CtS only. This noise factor is related to the inaccuracy of injection equipment that can be sufficiently well modeled using the zero-mean Gaussian distribution with a certain variance σ_I^2.
- *pressure-maintenance noise:* Pressure instability is related to velocity fluctuations along the transmission channel. This noise is due to imperfections in the

flow controlling device and characteristics of the transmission medium. Similar to injection-inaccuracy noise, these components are related to imperfections of one of the subsystems and can be modeled using a zero-mean Gaussian distribution with variance σ_P^2.

- *detection noise:* The detector output is also affected by non-ideal operation of the droplet detection apparatus. In fact, the metrics measured by the detection system are a random process evolving over time. Irrespective of the type of the method used for detection, it results in the deviation of the size of droplets and different inter-droplet duration. A number of studies suggest that this noise could be represented using a zero-mean Gaussian distribution with variance σ_D^2.

Injection-inaccuracy, pressure maintenance and detection noises can be denoted as by random variables $\mathcal{N}_I(0, \sigma_I^2)$, $\mathcal{N}_P(0, \sigma_P^2)$, and $\mathcal{N}_D(0, \sigma_D^2)$, respectively. Since these noises are produced by different elements of the system that do not interfere with each other, they are additive in nature and may add up either constructively or destructively at the receiver. Furthermore, it can be observed that injection-inaccuracy noise is source-induced noise, implying that its effect at the receiver depends on the distance between communicating systems l. This is taken into account by properly scaling the random variable by a coefficient $k_I(l)$. The second term is independent of the location of transceivers while the last one depends on a local phenomenon at the receiving side. Thus, the overall loss process follows a zero-mean Gaussian random variable with variance:

$$\sigma_E^2(l) = 0, k_I^2(l)\sigma_I^2 + \sigma_P^2 + \sigma_D^2. \tag{3.8}$$

Fig. 3.7 shows the noise density of the system that is normally distributed as explained above.

For OOK modulation, error in detection occurs when bit "1" is detected as "0" and vice versa. This happens when the threshold time slot for that particular bit is not fulfilled (too long or too short), causing false interpretation of the bit. The minimum time duration of one time slot for bit "1" (which corresponds to the minimum droplet length) is T_b and the minimum time duration of one time slot for bit "0" (which corresponds to the minimum distance between droplets) is T_{min}, where $T_b = T_{min} = D_H$. This value dictates the minimum possible operating frequency $F_c = \frac{1}{T_b}$. The calculation of SER for OOK and CtS modulations is similar and provided in subsequent discussion.

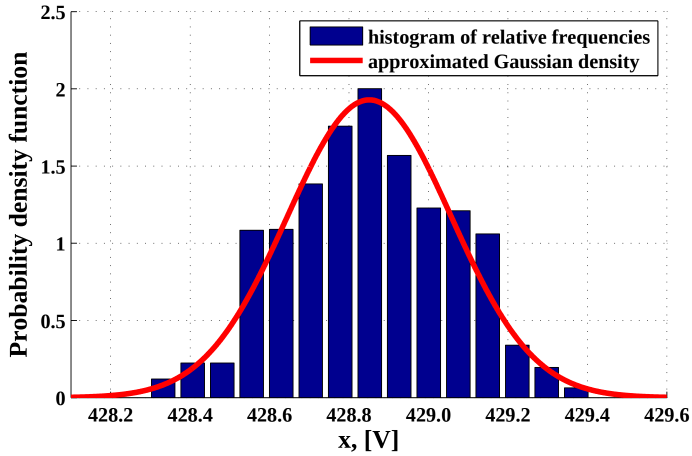


Figure 3.7 *Noise probability density function.*

Consider now CtS modulation. In a CtS transmission system whose operating frequency is F_c, the tolerable time bias is equal to half of one signal period, $\frac{T_c}{2}$. The detected symbol is received correctly if its values lies between $\pm\frac{T_c}{2}$. On the other hand, if it falls outside the given range, the symbol is considered to be erroneously received. Fig. 3.8 shows the probability density function for Gaussian noise. Here, the received symbol $\hat{x}$ is correctly detected when it lies in the "correct detection" region while received symbols outside that region indicates incorrect detection. It is necessary to recall that the detected data is the original data with the accumulated system noise, $\mathcal{N}_{err}(0, \sigma_{err}^2)$.

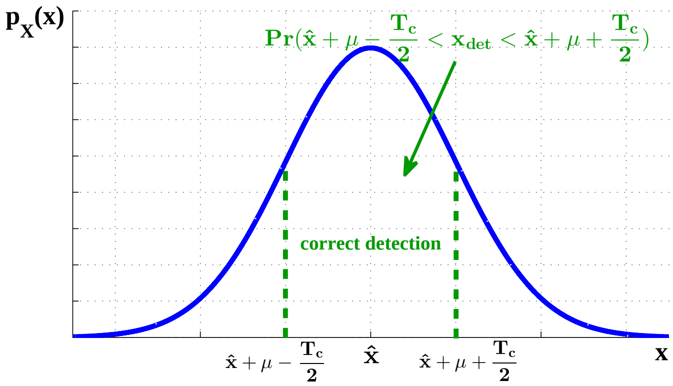


Figure 3.8 *Illustration of the symbol detection process.*

Using Q-function the SER is

$$p_E(l) = 2Pr\left(x > \hat{x} + \mu + \frac{T_c}{2}\right) = 2\left(\int_{\hat{x}+\mu+\frac{T_c}{2}}^{\infty} p_X(x)\,\mathrm{d}x\right) =$$

$$= 2Q\left(\frac{\left(\hat{x} + \mu + \frac{T_c}{2}\right) - \hat{x}}{\sigma_E(l)}\right) = 2Q\left(\frac{T_c}{2\sigma_E(l)}\right),$$

where $\hat{x}$ is the transmitted symbol.

The throughput of the system is defined as the fraction of symbols that are received correctly. Knowing the throughput of different modulations, R, and SER, p_E, the throughput is given by

$$G = R[1 - p_E(l)], \tag{3.9}$$

where R is the data rate.

3.3 Medium Access Control

In principle, microfluidic communication systems can rely upon similar principles for channel access as electromagnetic networks. Still, specifics of microfluidics do not allow them to be applied directly. However, unlike conventional electrical signaling in computer networks, the microfluidic channel provides unidirectional ordered transmission between the transmitters and receivers. Therefore, the design architecture of the system must take into account the order of the transmitter positions possibly, by arranging stations in a certain order and using channelization as a time division multiple access (TDMA), even for random access of stations to the medium. Both centralized and decentralized systems should implement certain algorithms ensuring both maximum channel utilization and collision avoidance.

3.3.1 Addressing

Addressing is an essential feature of the MAC layers allowing for communications between different pairs of stations. There are two ways to perform addressing in microfluidics environment. One approach is to use the classic approach enabling digital addressing in the header of each message. Another way is to exploit microfluidics properties using physical addressing.

Physical addressing

Fig. 3.9 illustrates the proposed addressing scheme that is applicable for multiple transmitter/receiver design of microfluidic communication systems. The addressing is provided by the length of the droplet itself. In CtS communications, these droplets represent the Start and Stop bits, while in OOK they are used to represent the duration of 0 and 1 symbols. Letting T_b be the minimum time slot allowed for the droplet, the length of the time slot corresponding to each particular source/destination pair is obtained by adding a certain fraction of T_b, Δ_{T_b}. Assuming N receivers and denoting the time slot length for the receiver i by $T_b^{[i]}$ produces the equation

$$T_b^{[i]} = T_b + [(i-1)\Delta_{T_b}], \qquad i = 1, 2, \ldots, N. \tag{3.10}$$

Application of the proposed scheme results in different sizes of droplets allowing for the distinction between different transmitters by simply measuring the duration of the droplet. Note that the value of Δ_{T_b} should be small enough to minimize the amount of control information, but sufficiently large for reliable detection of differences between droplet sizes. Consequently, as the number of transmitters increase, the amount of control information grows proportionally to the value of Δ_{T_b}, suggesting that the physical addressing is suitable for a small, possibly local network.

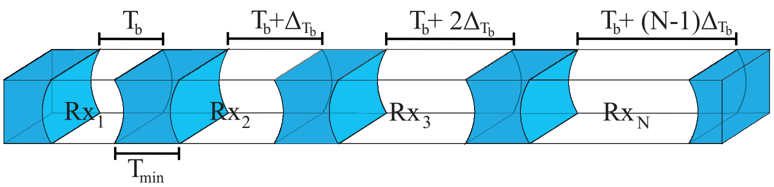


Figure 3.9 *Physical addressing in microfluidics communications.*

Digital addressing

In the digital addressing format, the address is represented by a certain value associated with each system on the microfluidic device. This value is encoded using either OOK or CtS modulation scheme and then sent as a header of the message. When using CtS modulation, this addressing can be used along with the piggyback transmission method. More destinations lead to larger addressing space. However, unlike physical addressing format, the increase in the number of transmitters does not result in a linear increase of the resources needed for it. Furthermore, digital addressing requires a fixed droplet size, resulting in simpler requirements for the droplet generation apparatus.

A unique receiver address is required in both local and distributed networks. It can be specified as a globally unique or locally unique. In the latter case, it must be supplemented with additional local address indicator. In general, digital type of addressing is more suitable for large distributed systems providing connectivity between local subnetworks. Physical addressing can be used a local environment at the MAC layer with digital addressing providing internetworking functionality.

3.3.2 Centralized System

In a centralized system, the medium is divided into time slots of length sufficient for sending the minimum payload size. There is a central unit (CU) that serves as a coordination entity, having the full knowledge of the system including traffic demands on the stations and scheduling transmission of end systems. This is accomplished by exclusively allocating the exact required number of time slots for each transmitter. All the transmitters are equipped with special wired interfaces to CU. These interfaces are used to notify CU about the transmission needs of end systems. The amount of information exchanged between end systems and CU may vary depending on a particular scheduling algorithm used at CU. Fig. 3.10 shows how the transmitters are connected to a CU which manages transmission channel access scheduling. In further detail, there are three main responsibilities of CU:

- Time - Length - Volume Conversion.
  When transmitters send requests to access the microchannel for message transmission, CU requires information about the destination address and total transmitted message. Afterwards, CU converts the information which is in decimal or hexadecimal data to time depending on operating frequency, then calculates the exact length based on flow speed, and finally correlates the length to required time and volume of droplet injection.

- Synchronization
  Since CU controls all the transmitters, CU handles the calculation and synchronization load. Maintaining synchronization for all the transmitters is important to avoid collisions during transmission.

- Droplet Position Tracking
  Droplet tracking by CU is accomplished by keeping records of droplet data in the memory temporarily until the droplet is out of the microfluidic system. This tracking corresponds to flow velocity and pressure in the system. Furthermore, position tracking is important for precise injection estimation time.

Depending on the amount of information exchanged via wired interfaces, there are two feasible scheduling schemes for centralized systems:

- Payload-based scheduling.
  In this scheme, CU requires the information about the payload size that are

at head of lines (HOL) at transmitting stations. The payload information is included in the transmit request sent by all the stations to CU. Based on these payloads, CU can authorize several transmitters to access the channel at the same time. Even though this scheme burdens CU, it maximizes the utilization of the transmission channel. In particular, when a transmitter tries to transmit decimal payload L_d, it sends a "transmit-request" to CU including the payload length information. Afterwards, CU replies by sending a "transmit-grant" to the transmitter when the channel has a vacant space of

$$L_T^i = 2[L_b + L_{\min} + \Delta_{T_b}(i-1)] + L_d, \tag{3.11}$$

where L_b denotes the minimum droplet length, Δ_{T_b} is one length increment unit from one transmitter to the previous one, i is the order of transmitter corresponding to the address, and $L_{\min}$ is the minimum distance between droplets to avoid coalescence.

- Maximum-time-based scheduling.
  In this scheme, CU does not require the knowledge of the HOL payload. The time allocation is based on the maximum required slot for the particular transmitter. CU has to ensure that at least the following space is vacant:

$$L_T^i = 2[L_b + L_{\min} + \Delta_{T_b}(i-1)] + L_{d\_max}, \tag{3.12}$$

where L_{d_max} is the threshold of payload length.

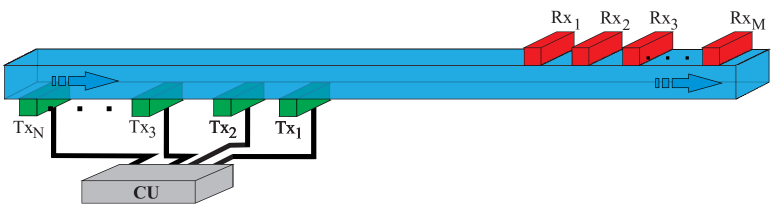


Figure 3.10 *Illustration of the centralized system.*

3.3.3 Decentralized System

When there is no control entity that may directly communicate and control transmissions of all the stations, a different approach for collision avoidance should be used. First, it should be noted that due to unidirectional ordered flow of data, a certain channelization scheme should be used for random access as well. The reason for this is that stations attached to a microfluidic device are not aware of the transmission of other stations until a droplet reaches their detectors. Thus, there is no effective algorithm to ensure detection or avoidance of collisions in an unslotted medium. Using *time division multiple access (TDMA)* channelization in random access environment may prevent the transmission of droplets in the same time slot using principles of classic *collision sense multiple access (CSMA)* protocols, as well as having less than the minimum required distance between the droplets causing coalescence. The combination of TDMA and *code division multiple access (CDMA)* in a microfluidic system may potentially guarantee that the transmitted droplet will not interfere with other transmissions.

Prior to droplet generation by a transmitter, carrier sensing is required to ensure that the time slot is free. Consider first a single receiving station. First, to enable carrier sensing there is a fundamental requirement on the minimum distance between the transmitter and the carrier sensing device/detector. This minimum distance ensures that coalescence or collision never occurs between existing bubble droplets in the microchannel and the newly generated bubble droplet. This distance is the sum of the maximum transmitted message distance for the corresponding transmitter and the minimum distance between the droplets. The maximum transmitted message may be different from one system to another, and it depends on the defined payload format. Thus, the detector distance from the corresponding transmitter follows

$$L_T^i = 2[L_b + L_{\min} + \Delta_{T_b}(i-1)] + L_{d\_max} + L_{cs}, \tag{3.13}$$

where L_{cs} is the required distance for carrier sensing purpose.

The parameter L_{d_max} is used for both equations (3.12) and (3.13) because they do not have prior knowledge of the exact length of required transmitted data. In this case, the longest possible transmitted data length should be anticipated. The parameter L_{cs} is included in Eq. 3.13, because unlike centralized system, transmitters in decentralized system do not have CU that controls and schedules the channel access. Fig. 3.13 illustrates one possible location of transmitter-receiver pairs in the microfluidic communication system.

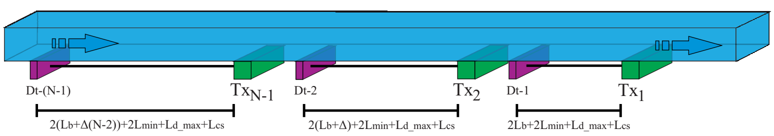


Figure 3.11 *Illustration of the minimum distance between stations.*

If the fairness of resource allocation is of interest, an additional algorithm is required. To illustrate this, if no additional effort is taken, a transmitter located at position i does not care about transmission opportunities with stations located at positions $i+1, i+2, \ldots, N$. Thus, a transmitter with the high traffic demands located at the beginning of the microfluidic device may occupy the transmission channel all the time, leaving others with no opportunity to access the channel. There are two ways to address this problem:

- **Relocation of stations.** If traffic demands on all stations are known prior to system implementation and the positions of stations are not strictly bounded to certain locations, their positions can be rearranged on the microfluidic device according to their traffic demands. Therefore, the transmitter whose traffic demand is lowest should be located at the beginning of the order along the direction of the flow. Furthermore, that transmitter should be assigned the longest address indicator length to minimize the channel utilization; this requirement is further discussed below. Consequently, the fairness of resource allocation depends on the relative traffic demands.

- **Priority-based access.** When traffic demands are not known in advance, or when positions of stations are strictly fixed, or when the system has already been implemented and there is no way to change the order of stations, priorities of channel access can be assigned to the stations. In general, the priority relation between the transmitters for the system should be chosen such that

$$P^{(1)} < P^{(2)} < P^{(3)} < \cdots < P^{(N-1)} < P^{(N)}, \tag{3.14}$$

  where $P^{(i)}$ is the priority of station i.

Fig. 3.12 shows the structure of time slots which includes slots for each transmitter in the system and synchronization slots indicating the beginning and the end of one transmission frame. The sync slot consists of a unique droplet and the minimum distance needed to avoid coalescence with the next droplet. For slots which bring information from transmitters, each of them consists of a uniform carrier sensing region which overlaps with the address indicator droplet. This carrier sensing region is divided into several smaller fields for each particular transmitter to begin its droplet addressing transmission. The purpose of this division is related to reasons of priority discussed above.

Consider one possible implementation of priority-based access system. In this case a decentralized system with controlled probability is based on a TDMA schedule, where each transmitter is allocated to a specific time slot of a transmission cycle. One full cycle of N transmitters consists of N time slots. The duration of a slot is

$$T_{slot} = 2(T_b^{[N]} + T_{\min}) + T_{d\_max} + T_{cs}. \tag{3.15}$$

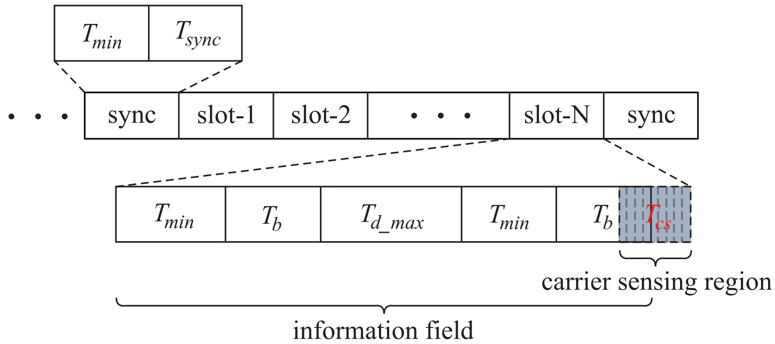


***Figure* 3.12** *Structure of time slots for TDMA scheduling.*

where $T_b^{[N]}$ is the time duration of maximum transmitted data by the N^{th} transmitter which is the transmitter whose address is the longest among all other transmitters, and T_{cs} is time duration for carrier sensing.

In order to maximize the occupancy of the channel, a transmitter senses all the time slots which, by default, belong to the preceding transmitters. If some of them are vacant, they can be used for data transmission by the stations. Observe that such behavior naturally leads to unfairness of the slots' allocation along the microfluidic device, as stations located in the middle of the order have more resources than those at the end or at the beginning. To address this issue, the following probabilistic access scheme is proposed. Let γ_i be assigned as the probability of occupying a preceding time slots by station i. Assuming that the packet generation probabilities of all the stations, p_j, $j = 1, 2, \ldots, N$, are the known optimal values of γ_i providing fairness of resource allocation are given by

$$\gamma_i = \frac{p_i}{\sum_{j=i}^{N} p_j}, \qquad i = 2, 3, \ldots, N \tag{3.16}$$

which is valid for arbitrary values of p_i.

Assuming constant $p_i = p$, $i = 1, 2 \ldots, N$ we have

$$\gamma_i = \frac{p}{\sum_{j=i}^{N} p} = \frac{1}{(N - i + 1)}, \qquad i = 2, 3, \ldots, N. \tag{3.17}$$

The minimum distance between transmitter/receiver pairs is

$$L_T^i = 2[L_b + L_{\min} + \Delta(N-1)] + L_{d\_max} + L_{cs}, \tag{3.18}$$

where N is the number of stations.

The system design is shown in Fig. 3.13.

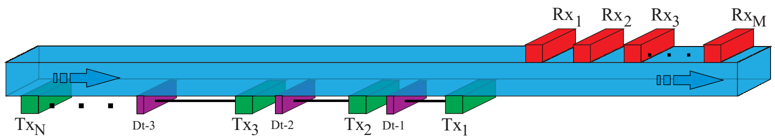


Figure* *3.13 *Illustration of decentralized system design.*

3.3.4 Performance Analysis

In a centralized system, where the CU manages the access to the transmission medium, throughput calculation is simple. Assuming a certain scheduling process at the CU (e.g. fair or weighted fair queuing) and equal traffic requirements for all the stations, the throughput for the entire system can be directly obtained. In ideal conditions, it equals the throughput of a microfluidic device while the per-station throughputs are the same. The deviations from the calculated values could only occur due to stochastic traffic patterns or imperfectness of fairness algorithm.

For PB, the CU has full knowledge of the payload size while in the case of MT, the maximum slot size common to all the stations is used. The guard slots between messages are all $L_b = 50\mu m$. All the transmitters are assumed to have an equal amount of traffic to send in each cycle. When implementing MAC protocols for microfluidics, the maximum decimal payload size should first be defined. By assigning this limit, the minimum distance between transmitters can be calculated using Eq.(3.12). Finally, the clock frequency must be high enough to achieve higher data transmission rates, but low enough to meet limitations of the hardware design (detector) and ensure acceptable BER. The minimum and maximum F_c can be calculated according to detector sensitivity. For the experiments, $F_c = 3$MHz was chosen. The simulation for this scenario is conducted in Sec. 4.3

3.3.5 Routing/switching

Microfluidics network design requires an element to direct the information to the correct path, in the case of multiple receivers. Additionally, since microfluidics is a flow driven system, at a certain distance, it might need some pressure repeater to maintain the flow rate. This system is conceptually similar to a repeater in classic communication systems. Depending on the addressing-payload scheme, there are two possible switching architectures:

- **Store-and-forward router.** This architecture should be used whenever the address and payload need to be detected and analyzed to decide upon the destination address. The routing logic has the knowledge of the routing table and manages the traffic among incoming and outgoing interfaces. This mechanism produces a delay, since the routing logic needs to receive all the data, analyze, and finally regenerate the data at the corresponding destination interface. Store-and-forward architecture is shown in Fig. 3.14.

- **Switch-through router.** This is a purely hydrodynamic architecture proposed in [11]. The principle of this routing mechanism is based on the difference in the pressure created by the droplet flowing in the channel. The first droplet in a train of two enters one default branch, resulting in a resistance change on the corresponding branch. Depending on the bypass channel size, the second informational droplet goes through either the same branch (if the first droplet has passed by the bypass channel) or the other branch (if the droplet has not passed by the bypass channel). In this case, the distance between droplets determines the routing decision. This mechanism is characterized by a shorter delay since it does not need to receive all the data to forward it to the intended interface. However, it also brings a number of limitations to network topology. These limitations include complex hardware based addressing network design and inflexibility in new network element addition. Fig. 3.15 illustrates switch-through router architecture.

The store-and-forward routing is suitable for both aforementioned addressing schemes, since it receives and analyzes all the information before regenerating and retransmitting it to the corresponding microfluidic channel. This mechanism is conceptually simple to implement. Furthermore, the modular architecture makes it feasible for extensions to a large number of interfaces supporting bigger networks. This could serve as a basic routing mechanism at the network layer. Unlike store-and-forward architecture, the switch-through routing exhibits a simple system architecture. The designed bypass channels are statically constructed for a particular local microfluidics environment. However, it implies that in the case of adding one more receiver, the entire local environment should be redesigned from scratch. The switch-through architecture can be used for static routing in small local networks.

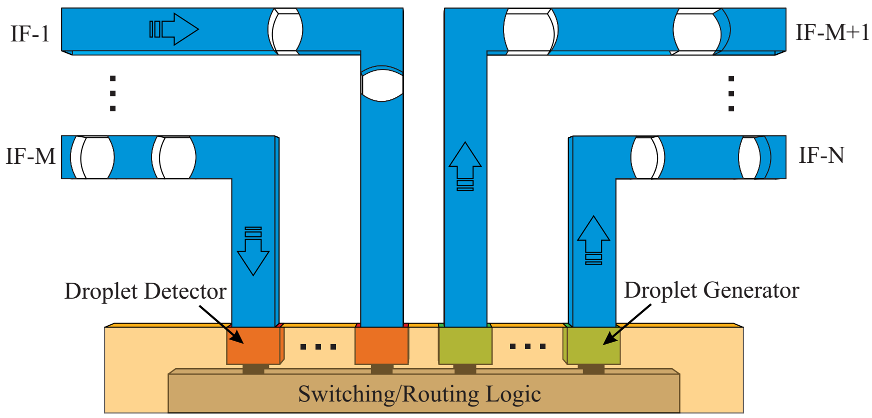


Figure 3.14 *Illustration of* store-and-forward routing *system.*

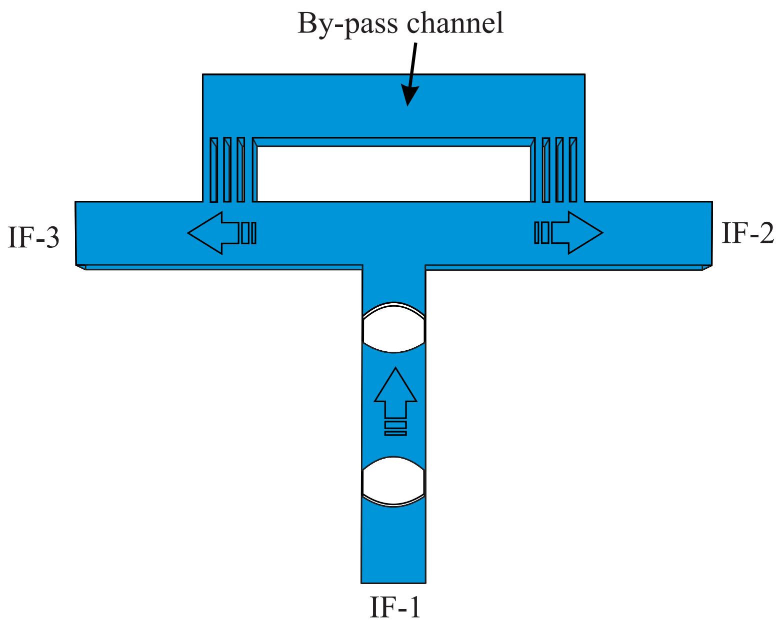


Figure 3.15 *Illustration of* switch-through routing *system.*

4. SIMULATIONS

In this chapter, the simulation work using MATLAB software is presented. Parameter simulation presented in this chapter is based on the theoretical calculation using all physical properties of the corresponding elements. The throughput simulations for both single and multiple transmitters-receivers are based on the theory that was discussed in Chapter. 3.

4.1 Parameter Simulation

In order to gain a better understanding of the pressure change behaviour along the microfluidic channel when an air droplet is injected into the channel, MATLAB simulations were conducted with the parameters defined in Table 4.1 for both hydrophilic and hydrophobic channels.

Table 4.1 *Initial variables*

Parameter	Value [Unit]	Description
Dynamic viscosity water	1E-3 [Ns/m^2]	Room temperature
Dynamic viscosity air	1.98E-3 [Ns/m^2]	
Diameter	50||100 [μm]	Channel hydraulic
Length	4 [cm]	Channel total length
Surface tension	7.28E-2	Room temperature
Contact angle hydrophobic	123°/94°	Advancing/Receding
Contact angle hydrophilic	21°/12°	
K	94	Dynamic contact angle
N	1	Number of droplet(s)
Initial pressure	10 [mbar]	

The results from the simulation are presented in Table 4.2 and Table 4.3. Table 4.2 corresponds to being no droplet injected into the microchannel, while in Table 4.3, the differences in pressure values are presented for a single droplet injected into the microchannel. On average, the total increase in the pressure for the hydrophilic case is lower than for the hydrophobic case. According to the simulation results presented in Table 4.2 and Table 4.3, where the fluid flows at a constant speed, and assuming constant contact angles, the capillary pressure loss is only influenced by the channel type, while the friction pressure loss is highly affected by the flow velocity and the "air droplet vs water" occupancy.

Table 4.2 *Simulation result with no droplet*

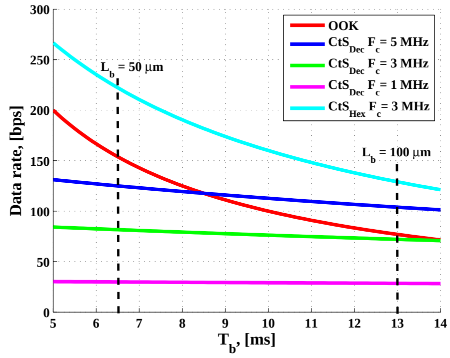
Channel Diameter [μm]	ΔP [$mbar$]	Q [$\mu l/s$]	v [mm/s]
50	10	0.0038	1.53
	50	0.0192	7.667
	500	0.1917	76.67
100	10	0.0614	6.1359
	50	0.3068	30.6796
	500	3.0680	306.7962

Table 4.3 *Simulation result with one droplet*

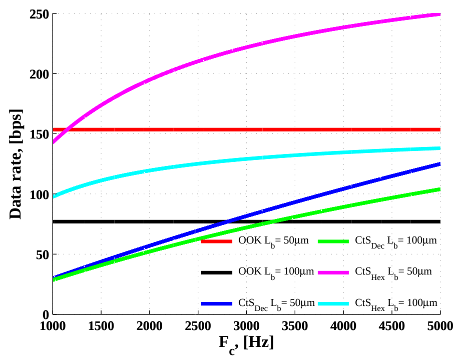
Channel Type	Channel Diameter [μm]	$\Delta P_{capillary}$ [$mbar$]	$\Delta P_{friction}$ [$mbar$]	ΔP_{total} [$mbar$]	v [mm/s]
Hydrophobic	50	27.6499	9.9877	37.637	1.53
		27.6209	49.9387	77.560	7.667
		27.2940	499.3874	526.68	76.67
	100	13.8146	9.9750	23.7896	6.1359
		13.7585	49.8750	63.6335	30.6796
		13.1244	498.7500	511.8744	306.7962
Hydrophilic	50	2.5956	9.9877	12.583	1.53
		2.5957	49.9387	52.534	7.667
		2.5937	499.3874	501.98	76.67
	100	1.2983	9.9750	11.2733	6.1359
		1.3002	49.8750	51.1752	30.6796
		1.3015	498.7500	500.0515	306.7962

4.2 Single Transmitter - Single Receiver

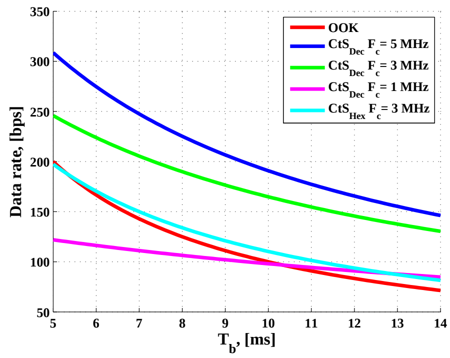
The performance of both OOK and CtS modulations is shown in Fig. 4.1. For the CtS scheme, continuous transmission property for both SSS and PB and two encoding schemes were considered. The transmitted payload consisted of 5 and 8 binary bits. The data rate as a function of the droplet duration is shown in Fig. 4.1(a) and 4.1(c). As expected, the performance of all modulations drops when the droplet size becomes bigger. It is important to note that the performance of OOK for the minimum droplet size $L_b = 50\mu m$ (recall that it coincides with the diameter of the microfluidic device) is second highest among all CtS schemes considered. The optimum message size for both decimal and hexadecimal base number payload is



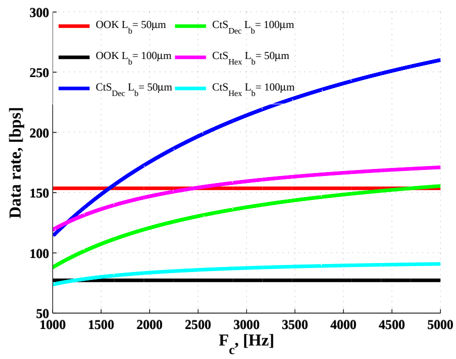
(a) Data rate as a function of T_b (Payload size = 8 bits).



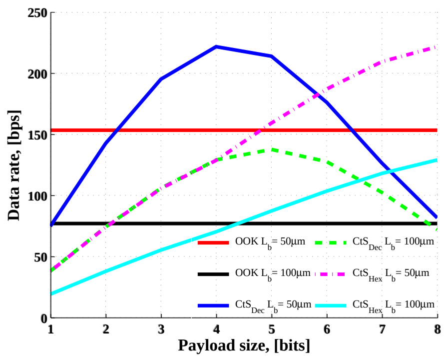
(b) Data rate as a function of F_c (Payload size = 8 bits).



(c) Data rate as a function of T_b (Payload size = 5 bits).



(d) Data rate as a function of F_c (Payload size = 5 bits).



(e) Data rate as a function of payload.

Figure 4.1 *Performance of OOK and CtS modulation schemes in PB regime.*

illustrated in Fig. 4.1(e). Each encoding scheme exhibits different performance depending on the message size. In fact, CtS with operating frequency $F_c = 3$MHz outperforms OOK on its optimum message size transmission. The reason for such behavior is that in CtS it is still necessary to use two droplets for start and stop symbols. For larger payload sizes, better performance gains are expected for CtS. Also, the increase in L_b affects OOK more than CtS.

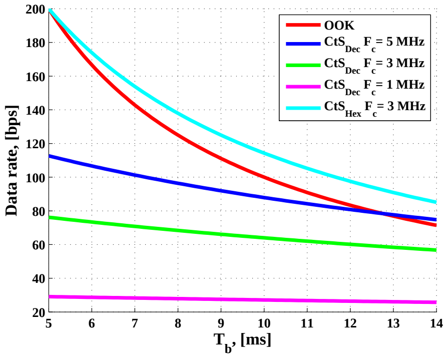
Fig. 4.1(b) and 4.1(d) demonstrate the achieved data rates as a function of the operating frequency, F_c, for both OOK and CtS for the droplet sizes $50\mu m$ and $100\mu m$. The payload was again set to 5 and 8 binary bits. Since the operational frequency affects CtS performance only, the data rate of OOK is constant. However, for $L_b = 50\mu m$, the performance of OOK is higher than for all CtS schemes except one particular CtS depending on the corresponding transmitted payload size (CtS Decimal for 5 bit transmission and CtS Hexadecimal for 8 bit transmission) across majority of the frequency domain. Here, it is also of interest to notice that the performance is again dependent on optimum transmitted message size. Finally, the achieved data rate for CtS and OOK as a function of the message size (in terms of binary bits) is shown in Fig. 4.1(e) for the droplet sizes $50\mu m$ and $100\mu m$, and operating frequency $F_c = 3$MHz. This figure is of interest, as it shows that for a CtS scheme there is an optimal message size allowing the highest data transmission rate to be achieved. This optimal size is a function of the minimum droplet L_b. OOK data rate is independent of the droplet size.

Performance of OOK and CtS modulations operating in SSS regime is demonstrated in Fig. 4.2. Qualitatively, the behavior of all dependencies is similar to that of CtS PB. However, it is important to note that quantitatively OOK performs even better in the SSS regime compared to the CtS regime. Only CtS operating at 3MHz and transmitting optimum message size performs better than OOK.

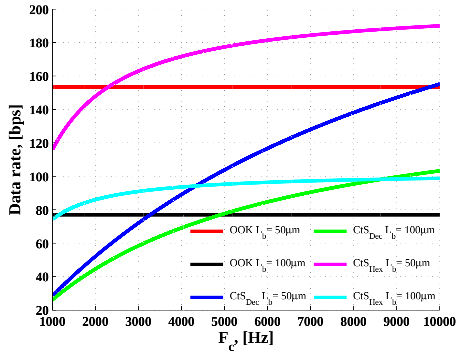
In general, the PB scheme exhibits better performance than the SSS scheme due to the structure of the message discussed in Subsection. 3.2.1. SSS needs separate indicator bits (start and stop) while PB only requires one common indicator bit (start/stop). OOK performance dominates for low payload size transmission because CtS has a constant length of indicator bits, which must exist even though it only wants to send one binary message. From this simulation, it can be concluded that the CtS scheme is suitable for the implementation of the delivery of a message containing a high digit binary number, whereas OOK scheme is better for the delivery of a message which consists of a low digit binary number.

4.3 Multiple Transmitters - Multiple Receivers

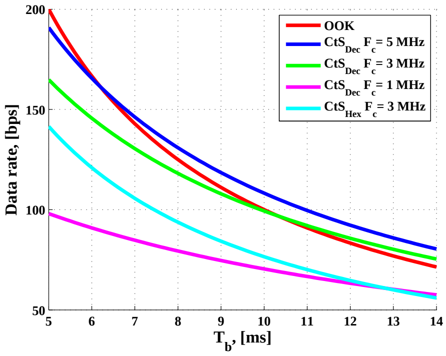
Fig. 4.3 demonstrates overall throughput for two and three transmitter system design with centralized payload-based (PB) scheduling and maximum-time-based (MT) scheduling for F_c = 3MHz. The scenario of this simulation is that each transmitter sends a certain payload size with an equal number of transmission cycles. For a decentralized system, it has equal data rate as a maximum-time-base scheme



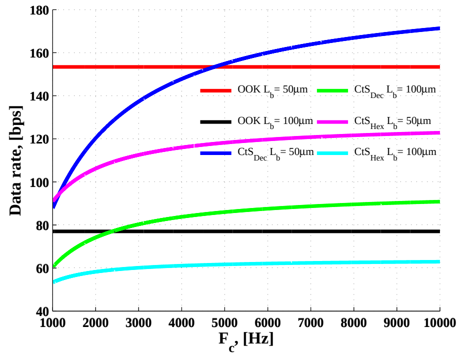
(a) Data rate as a function of T_b (Payload size = 8 bits).



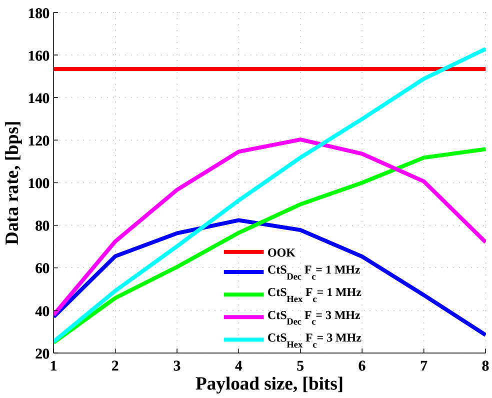
(b) Data rate as a function of F_c (Payload size = 8 bits).



(c) Data rate as a function of T_b (Payload size = 5 bits).



(d) Data rate as a function of F_c (Payload size = 5 bits).



(e) Data rate as a function of payload.

Figure 4.2 *Performance of OOK and CtS SSS modulation schemes.*

due to its transmission characteristics of allocating a certain uniform maximum space for one transmission slot as explained in Sec.3.3.

The simulation result illustrates the fundamental difference between PB and MT schemes. The maximum allocation for transmitted payload by the MT scheme causes a resource allocation waste while the exact payload allocation by the PB scheme maximizes the available transmission resources. The data rate graphs for both of the schemes converge at the maximum transmitted payload (15 bits), this shows the condition that when maximum payload size is transmitted, the data rates for both schemes are equal. When the number of transmitters increases, the overall throughput for both schemes decreases. This occurs due to the increasing space occupied by start and stop bit indicators.

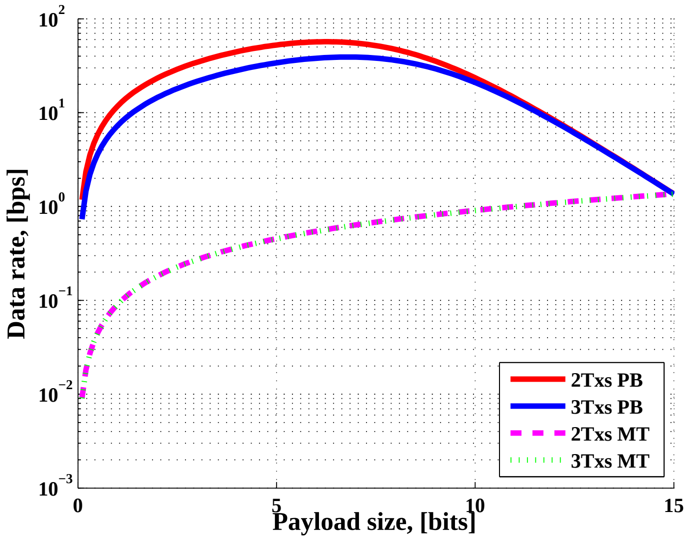


Figure *4.3 Overall throughput as a function of transmitted payload size.*

4.4 Decentralized System Fairness

For a decentralized system, ensuring fairness among the stations the per-station data rate calculation is more complex. Below, the evaluation of the performance of the proposed algorithm on Subsec. 3.3.3 is conducted using the simulation approach. In this simulation (Fig. 4.4), ten transmitters are used to analyze the fairness of the system for one million transmission cycles. *Jain fairness index* indicates the fairness measurement of the system and is calculated as:

$$\mathcal{J}(x_1, x_2, \ldots, x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} {x_i}^2} \tag{4.1}$$

where n is the total amount of transmitters, and x_i is the throughput for the i^{th} transmitter. For this fairness of a decentralized system simulation, the data generation for all transmitters is equal. The speed of data generation level is average. This means that there is a certain period when the transmitters have a data queue on their buffers. On the other hand, there is also a certain period when the transmitters have sufficient resources to dispatch all the queued data and clear their buffers. From this simulation, the Jain fairness index can be evaluated for this transmission algorithm. The index is equal to "1" which means the system is fair from the throughput and resource allocation point of view.

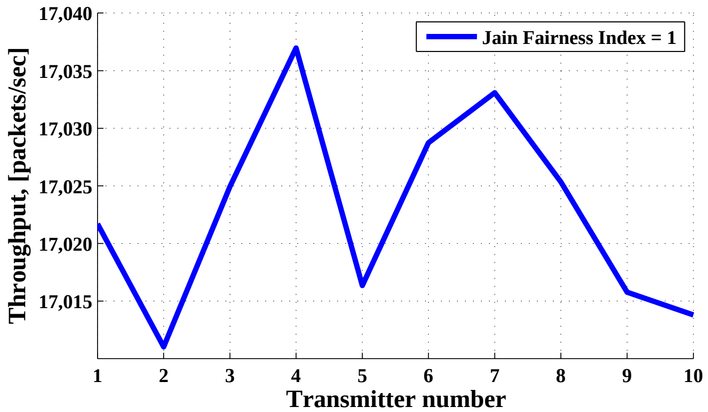


Figure 4.4 *Per-station throughput.*

5. CONCLUSION

In this thesis, the protocols that can support microfluidic communication system are investigated. The noise contributing to the overall system is investigated; this includes noise level increment related to transmitted data modulation, transmission access priorities depending on relative location of one transmitter to another, and coalescence possibility between microdroplets. Lastly, protocols are designed so that it could minimize the effects of the aggregate noise on the microfluidic communication system.

In Chapter. 2, a microfluidic communication system design is elaborated from the perspective of hardware. The choice of each component to construct the system determines the overall system implementation since they contribute to overall system noise. These choices of materials and methods for system implementation require more assessment and investigation in the laboratory.

The proposal of communication protocols for microfluidics communication system is discussed on Chapter. 3. For the physical layer, the focus is developing a protocols based on CtS modulation scheme due to its ability to represent each message part (address and payload) is more simple than in to OOK. Moreover, it is related to the physical properties of microfluidics where more droplets in the channel may cause increased pressure and flow speed fluctuation. The level crossing method is sufficient for detection data processing when the droplet and continuous flow have significant metric measurement level difference. Centralized and decentralized (random access) systems are introduced with their detailed system requirements. A centralized system enables maximum resource usage by exact time period allocation and scheduling for data transmission, with all transmission activities controlled by the CU. In contrast, a decentralized system always allocates the maximum time period even for transmitting a small amount of data since it needs to anticipate maximum data transmission possibility. A transmission fairness issue may arise, since there is a priority difference among transmitters due to their locations in the channel, and the concept of TDMA is used to overcome this issue. Regarding the addressing method, physical addressing is more effective and simple in a smaller scale network, however it does not restrict the possibility of a digital addressing method in the future. A store-and-forward router can support switching functionality and also act as repeater. This type of router is more viable for implementation when compared to a switch-through router, which is more suitable for a less dynamic network configuration.

Finally, in Chapter. 4, software simulations have been conducted to analyze the proposed design. In continuous data transmission simulations, for both SSS and PB schemes, only CtS with particular optimum message size can outperform OOK data transmission rate. This happens due to start, stop, and separation bits needed for CtS. For multiple transmitters and receivers, the PB scheme outperforms MT and decentralized systems due to its space allocation structure of transmitted data. From the perspective of fairness, the proposed algorithm (based on its probability to complement slotted structure for a decentralized system) is able to perform well.

The proposed design and protocols for microfluidic communication are still in the initial state. This is an original proposal that presents a communication protocol stack that can be applied to microfluidic channels. The hardware evolution has a significant role in system performance improvement. There is still plenty of room for research in this area to polish the concept of communication in microfluidics, for example in routing, noise suppression, and error correction. In the future, with standardized communication protocol for microfluidics, microfluidic application developers will be able to easily integrate communication functionality into their applications. For example, the implementation of a liquid microcooling system can be taken to the next level, by integrating data transmission capabilities.

BIBLIOGRAPHY

[1] A. R. Abate, T. Hung, R. A. Sperling, P. Mary, A. Rotem, J. J. Agresti, M. A. Weiner, and D. A. Weitz, "DNA sequence analysis with droplet-based microfluidics," *Lab on a Chip*, vol. 13, no. 24, pp. 4864–4869, 2013.

[2] I. F. Akyildiz, F. Brunetti, and C. Blázquez, "Nanonetworks: A new communication paradigm," *Computer Networks*, vol. 52, no. 12, pp. 2260–2279, 2008.

[3] J. Berthier, *Micro-Drops and Digital Microfluidics*, ser. Micro and Nano Technologies. Elsevier Science, 2012. [Online]. Available: http://books.google.fi/books?id=ojmmTl-T8xUC

[4] B. B. Bhattacharya, S. Roy, and S. Bhattacharjee, "Algorithmic challenges in digital microfluidic biochips: Protocols, design, and test," in *Applied Algorithms*. Springer, 2014, pp. 1–16.

[5] A. Bicen and I. Akyildiz, "End-to-end Propagation Noise and Memory Analysis for Molecular Communication over Microfluidic Channels," 2014.

[6] A. Biral and A. Zanella, "Introducing purely hydrodynamic networking functionalities into microfluidic systems," *Nano Communication Networks*, vol. 4, no. 4, pp. 205–215, 2013.

[7] Z. Cao, F. Chen, N. Bao, H. He, P. Xu, S. Jana, S. Jung, H. Lian, and C. Lu, "Droplet sorting based on the number of encapsulated particles using a solenoid valve," *Lab on a chip*, vol. 13, no. 1, pp. 171–178, 2013.

[8] J. Čemažar, D. Miklavčič, and T. Kotnik, "Microfluidic devices for manipulation, modification and characterization of biological cells in electric fields–a review," *Electronic Components and Materials*, vol. 43, no. 3, pp. 143–161, 2013.

[9] Y. P. Chen, D. Wang, and J. Zhang, "Variable-base tacit communication: a new energy efficient communication scheme for sensor networks," in *Proceedings of the first international conference on Integrated internet ad hoc and sensor networks*, 2006, p. 27.

[10] C. Dalmay, J. Villemejane, V. Joubert, A. Silve, D. Arnaud-Cormos, O. Français, L. M. Mir, P. Leveque, and B. Le Pioufle, "A microfluidic biochip for the nanoporation of living cells," *Biosensors and Bioelectronics*, vol. 26, no. 12, pp. 4649–4655, 2011.

[11] E. De Leo, L. Donvito, L. Galluccio, A. Lombardo, G. Morabito, and L. M. Zanoli, "Communications and switching in microfluidic systems: Pure hydrodynamic control for networking labs-on-a-chip," *IEEE transactions on communications*, vol. 61, no. 11, pp. 4663–4677, 2013.

[12] C. Elbuken, T. Glawdel, D. Chan, and C. L. Ren, "Detection of microdroplet size and speed using capacitive sensors," *Sensors and Actuators A: Physical*, vol. 171, no. 2, pp. 55–62, 2011.

[13] A. Ernst, W. Streule, N. Schmitt, R. Zengerle, and P. Koltay, "A capacitive sensor for non-contact nanoliter droplet detection," *Sensors and Actuators A: Physical*, vol. 153, no. 1, pp. 57–63, 2009.

[14] M. J. Fuerstman, P. Garstecki, and G. M. Whitesides, "Coding/decoding and reversibility of droplet trains in microfluidic networks," *Science*, vol. 315, no. 5813, pp. 828–832, 2007.

[15] P. Garstecki, M. J. Fuerstman, H. A. Stone, and G. M. Whitesides, "Formation of droplets and bubbles in a microfluidic t-junction - scaling and mechanism of break-up," *Lab on a Chip*, vol. 6, no. 3, pp. 437–446, 2006.

[16] H. Gu, M. H. Duits, and F. Mugele, "Droplets formation and merging in two-phase flow microfluidics," *International journal of molecular sciences*, vol. 12, no. 4, pp. 2572–2597, 2011.

[17] W. Gu, P. Cheng, A. Ghosh, Y. Liao, B. Liao, A. Beskok, and Z. Hao, "A polymer-based microfluidic resistive sensor for detecting distributed loads," in *ASME 2012 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, 2012, pp. 539–548.

[18] S. Hemmilä, J. V. Cauich-Rodríguez, J. Kreutzer, and P. Kallio, "Rapid, simple, and cost-effective treatments to achieve long-term hydrophilic pdms surfaces," *Applied Surface Science*, vol. 258, no. 24, pp. 9864–9875, 2012.

[19] I. Ieropoulos, J. Greenman, C. Melhuish, and I. Horsfield, "Ecobot-III-A Robot with Guts." in *ALIFE*, 2010, pp. 733–740.

[20] ITU-T, "Information technology - open systems interconnection - basic reference model: The basic model," International Telecommunication Union, Geneva, Recommendation X.200, July 1994.

[21] B. Krishnaswamy, C. M. Henegar, J. P. Bardill, D. Russakow, G. L. Holst, B. K. Hammer, C. R. Forest, and R. Sivakumar, "When bacteria talk: Time

elapse communication for super-slow networks," in *Communications (ICC), 2013 IEEE International Conference on.* IEEE, 2013, pp. 6348–6353.

[22] Y. Liu, M. Tian, and H. Zhang, "Microfluidics for synthesis of peptide-based pet tracers," *BioMed research international*, vol. 2013, 2013.

[23] P. Novo, V. Chu, and J. P. Conde, "Integrated fluorescence detection of labeled biomolecules using a prism-like pdms microfluidic chip and lateral light excitation," *Lab on a Chip*, vol. 14, no. 12, pp. 1991–1995, 2014.

[24] Proakis, *Digital Communications 5th Edition.* McGraw Hill, 2007.

[25] P.-H. Yuh, C.-L. Yang, and Y.-W. Chang, "Bioroute: A network-flow-based routing algorithm for the synthesis of digital microfluidic biochips," *Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on*, vol. 27, no. 11, pp. 1928–1941, 2008.

[26] C. Zhang, D. Xing, and Y. Li, "Micropumps, microvalves, and micromixers within pcr microfluidic chips: advances and trends," *Biotechnology advances*, vol. 25, no. 5, pp. 483–514, 2007.

[27] Y. Zhu and R. Sivakumar, "Challenges: communication through silence in wireless sensor networks," in *Proceedings of the 11th annual international conference on Mobile computing and networking.* ACM, 2005, pp. 140–147.